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Generating curvature perturbations with MSSM flat directions

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Abstract

We consider the possibility that chaotic inflation is driven by a Minimal Supersymmetric Standard Model (MSSM) flat direction or a sneutrino. The discrepancy between our present study and past studies is in the mechanism for generating the curvature perturbations. We consider curvature perturbations generated by instant preheating at the end of inflation, instead of a conventional curvature perturbation generated by a fluctuation related to an inflaton field. Our simple mechanism relaxes some serious constraints that appeared in past studies, making chaotic inflation driven by a MSSM flat direction or a sneutrino more plausible.

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1 Introduction

In the standard scenario of the inflationary Universe, the observed density perturbations are assumed to be produced by a light inflaton rolling down its potential during inflation. This “standard mechanism” of generating the curvature perturbation has been investigated by many authors [1]. Although it may be possible to construct some inflationary scenarios with this mechanism, it is not always easy to find a situation where an inflaton field appears naturally in the Grand Unified Theory (GUT) of particle physics, and at the same time has all the required conditions for inflation satisfied without fine-tunings or an additional hidden sector for inflation. In this paper we focus our attention on inflationary models in which a MSSM flat direction or a sneutrino plays the role of an inflaton. As will be presented in sec. 2, past studies on MSSM (or sneutrino) inflation were studied on the basis of a conventional mechanism of generating the curvature perturbations related to fluctuations of an inflaton. The conditions required for the coupling constants in the theory were very severe, demanding fine-tunings of the MSSM parameters. Hence, our question in this paper is very simple. Is it possible to solve or relax the above-mentioned conditions with a new mechanism for generating curvature perturbations?

Recently, a new inflationary paradigm has been developed where the conventional slow-roll picture does not play an essential role in generating the curvature perturbation. Along the lines of this “new inflationary paradigm”, we will consider a scenario where isocurvature perturbation of a light field is converted into the curvature perturbation at the time of instant preheating that occurs at the end of inflation, when the inflaton kinetic energy is significant. The most important point is that in this new inflationary paradigm the light field is not identified with the inflaton. The “light field” is decoupled from the inflationary dynamics during inflation, but it plays a significant role at reheating. The idea of a “light field” has already been investigated by many authors. Although there have been many attempts in this direction, the most famous examples would be the curvaton models [2, 3]. In the curvaton models, the origin of the large-scale curvature perturbation in the Universe is the late-decay of a massive scalar field that is called the “curvaton”. The curvaton paradigm has attracted much attention because it was thought to have obvious

advantages. For example, since the curvaton is independent of the inflaton field, there was the hope [4] that the curvaton scenario, especially in models with a low inflationary scale, could cure serious fine-tunings associated with the inflation models.² Despite the advantages of the curvaton scenario, Lyth suggested [7] that there is a strong bound for the Hubble parameter during inflation, even when the curvatons are introduced to the model. The bound obtained by Lyth [7] was critical, but it was later suggested by Matsuda [8] that the difficulty could be avoided if an additional inflationary expansion or a phase transition were present [9]. At first this solution seemed quite generic since there could be several phase transitions after inflation, but it was later discovered that this scenario requires many additional components. It is possible to solve the problem [7] with the idea suggested in Ref.[8], but then one cannot escape from uncertainties coming from the additional components. Besides the curvatons, the problem of uncertainties is common in almost all the inflationary scenarios that require fields that cannot appear in the Standard Model(SM). This is one of our motivations to study inflation that occurs on MSSM or sneutrino direction.

Another idea in this inflationary paradigm was investigated most recently by Lyth [10], where an argument was presented that the density perturbations can be generated “at the end of inflation” by the fluctuations of the number of e-foldings induced by the fluctuations related to a light scalar field other than the inflaton.³ An important advantage in the new mechanism is that there are no such stringent conditions coming from the requirement of (1) late-time curvaton dominance, and (2) successful reheating. Using this new idea, we studied, in Ref.[12, 13], the generation of curvature perturbations in fast-roll inflationary models. Since the hybrid-type potential appears naturally in brane-antibrane inflation and a light field may generically appear in brane inflationary models, the new mechanism is very useful in brane inflationary models. The most obvious example along these lines would be throat inflation, where a light field related to an enhanced isometry appears

²Many attempts have been made to construct realistic models with low inflationary scale[5], where cosmological defects might play an essential role[6]. In spite of the merits of these low-scale inflationary models, an ultimate solution has not yet been found.

³See also Ref.[11], where different models for generating the curvature perturbation were proposed along the lines of this “new inflationary paradigm”. Although we do not mention these alternative ideas, these ideas are equally important.

“at a distance” from the moving brane as we have proposed in Ref.[12] and [13].⁴ On the other hand, if the brane motion is relativistic, or the kinetic energy of the inflaton is significant, the so-called “instant preheating” should be significant in such analysis. In order to solve this problem, we proposed in Ref.[15] an alternative mechanism along the lines of this “new inflationary paradigm”. This is a generic mechanism for generating the curvature perturbation that works with an instant preheating at the end of inflaton. The instant preheating should be equipped with a light field, whose expectation value plays the role of an impact parameter. This alternative mechanism of generating curvature perturbation at the end of inflaton will be quite useful in MSSM inflationary models, since in such models instant preheating is a natural mechanism of reheating and at the same time there are many flat directions that can play the role of the light field.

In this paper we will examine whether the serious conditions that have been required in past studies can be relaxed by introducing the new mechanism we presented in Ref.[15]. It will be helpful to conduct a short review of previous attempts in this direction showing why it was difficult to make an inflationary model on a MSSM (or sneutrino) direction. Conclusions are given in sec. 3. We will show that one can solve or dramatically relax the serious conditions that were found in past studies, by introducing this new mechanism to the theory.

2 How to relax fine-tunings in MSSM and sneutrino inflation

2.1 New mechanism

Generically a multi-field inflationary model is described by the background inflaton fields $\phi_i(t)$ which evolve according to the system of coupled differential equations

$$\ddot{\phi}_i + 3H\dot{\phi}_i + \frac{\partial V}{\partial \phi_i} = 0, \quad i = 1, \dots, n \quad (2.1)$$

and

$$H^2 = \frac{8\pi}{3M_p^2} \left[\sum_i \frac{\dot{\phi}_i^2}{2} + V \right]. \quad (2.2)$$

⁴Riotto and Lyth made another useful discussions on this point[14].

Without losing general applicability, we can discuss our mechanism with two orthogonal fields, ϕ_1 and ϕ_2 , where ϕ_1 is a conventional inflaton field and ϕ_2 is the “light field”. The potential $V(\phi_1, \phi_2)$ is characterized by a hierarchy between the masses of the fields, and can be modeled by

$$V(\phi_1, \phi_2) = \frac{m_1^2}{2}\phi_1^2 + \frac{m_2^2}{2}\phi_2^2, \quad (2.3)$$

where $m_1 \simeq O(H)$ and $m_2 \ll m_1$.⁵ We consider the instant preheating model[17] as the process through which the inflaton decays into lighter particles. The typical coupling to the preheat field χ is written as

$$\mathcal{L} = \frac{g}{2}(\phi_1^2 + \phi_2^2)\chi^2, \quad (2.4)$$

which gives a mass $m_\chi = g\sqrt{\phi_1^2 + \phi_2^2}$ to the preheat field. Applying the result obtained in Ref.[17], the comoving number density n_χ of the preheat field χ produced during the first half-oscillation of ϕ_1 becomes

$$n_\chi \simeq \frac{(g|\dot{\phi}_1(t_*)|)^{3/2}}{8\pi^3} \exp \left[-\frac{\pi g|\phi_2(t_*)|^2}{|\dot{\phi}_1(t_*)|} \right], \quad (2.5)$$

where t_* is the time when the inflaton ϕ_1 reaches its minimum potential at $\phi_1 = 0$ and where the light field ϕ_2 may still have an expectation value $\phi_2(t_*) \neq 0$. We used $\dot{\phi}_2 = 0$ and $\delta\dot{\phi}_2 = 0$ to derive Eq.(2.5). To obtain an estimate of the curvature perturbation through Eq.(2.5), we need to write down an expression for $\delta n_\chi/n_\chi$;

$$\frac{\delta n_\chi}{n_\chi} = \frac{2\pi g|\phi_2(t_*)|^2}{|\dot{\phi}_1(t_*)|} \frac{|\delta\phi_2(t_*)|}{|\phi_2(t_*)|}, \quad (2.6)$$

where it is assumed that $|\delta\phi_2(t_*)| \ll |\phi_2(t_*)|$ so that we can neglect higher terms. To determine the curvature perturbation produced during the decay process of the preheat field χ , it is sufficient to note that the generated energy density is proportional to the comoving number density n_χ . Assuming a smooth decay process of the preheat field, the curvature perturbation ζ generated during the instant preheating is

$$\zeta \simeq \alpha \frac{\delta n_\chi}{n_\chi}, \quad (2.7)$$

where α is a constant whose numerical value depends on the redshift of the particle produced. Since the field ϕ_2 is approximately massless during inflation, the value of

⁵A different approach has been given by Kolb et.al.[16], who assumed $m_2 \simeq m_1$

the fluctuation is given by $\delta\phi_2 \simeq H_I/2\pi \simeq V_I^{1/2}/(2\sqrt{3}\pi M_p)$. In the simplest case of a single-stage inflationary model, the curvature perturbation ζ is approximately

$$\zeta \simeq \frac{\alpha 2\pi g |\phi_2(t_*)|^2 |\delta\phi_2(t_*)|}{|\dot{\phi}_1(t_*)| |\phi_2(t_*)|}. \quad (2.8)$$

Since the field ϕ_2 is very light, it is possible to have $\phi_2(t_i) \simeq \phi_2(t_*)$, where t_i is the time when the inflaton ϕ_2 starts fast-rolling. As we are considering a case where the kinetic energy of the inflaton field ϕ_1 is significant at the time of preheating,

$$\dot{\phi}_1(t_*)^2 \simeq m^2 |\phi_1(t_i)|^2 \simeq H_I^2 M_p^2 \quad (2.9)$$

is a natural consequence. We must also consider the condition for the efficient production of the preheat field χ , which is written as

$$m_\chi^2 \simeq g |\phi_2(t_*)|^2 < \dot{\phi}_1(t_*). \quad (2.10)$$

Considering the above conditions, we found a relation

$$\zeta \simeq \frac{\alpha 2\pi g |\phi_2(t_*)|^2 |\delta\phi_2|}{|\dot{\phi}_1(t_*)| |\phi_2(t_*)|} \simeq \frac{\alpha g |\phi_2(t_*)|}{M_p} < \frac{\alpha g^{1/2} \sqrt{m\phi_1(t_i)}}{M_p} \simeq \alpha \sqrt{\frac{10m}{M_p}}. \quad (2.11)$$

Here α depends on the redshift of the final product. In the present case, since we are considering instant preheating in a MSSM direction, the final product is assumed to be massless ($\alpha = 1/4$). The ratio between ϕ_2 and $\delta\phi_2$ is not a parameter of the underlying theory, but it is an initial condition at the beginning of inflation. This is the new mechanism that we will consider in this paper. With this new mechanism for generating curvature perturbations, is it possible to solve or relax the conditions obtained in past studies on MSSM and sneutrino inflation?

2.2 Quartic potential

There may be a rather peculiar possibility for chaotic inflation with MSSM direction, which is to use a D-flat but not an F-flat direction[18]. In this scenario we consider quartic potential

$$V(\phi) = \frac{\lambda}{4} \phi^4, \quad (2.12)$$

where λ is a dimensionless coupling constant. The value of the inflaton field when a fluctuation denoted by k exits horizon is related to the number of e-foldings N_k elapsed after the horizon exit as

$$\phi_k \simeq \sqrt{N_k} M_p. \quad (2.13)$$

Hence, using a standard calculation[1], the curvature perturbation at the horizon exit is evaluated as

$$\zeta_k \simeq \sqrt{\lambda} N_k^{3/2} \simeq 10^{-5}, \quad (2.14)$$

which means that normalization of the primordial density fluctuation requires a tiny value for the constant $\lambda \sim 10^{-13}$ [1]. One way to solve this problem is to expect an approximate symmetry. If one wants to consider a model in which the inflaton field ϕ is related to a D-flat direction in MSSM, one should remember that Yukawa interactions in MSSM lift some of the D-flat directions. Then the coupling constant λ is given by $\lambda \simeq y^2$, where the Yukawa coupling constant is denoted by y . In the original study[18] it was suggested that the relevant Yukawa coupling must be many orders of magnitude below unity. To be more precise, the standard calculation suggests that MSSM D-flat inflation might be possible if $\lambda \simeq y^2 \simeq 10^{-13}$. Choosing an R-parity breaking Yukawa coupling, there is a strict “upper” bound for y . This condition nearly (but perhaps not entirely) contradicts to the known limits for the R-parity violating Yukawa couplings. Except for a fine-tuning, smaller λ is more favorable if it is related to an R-parity breaking Yukawa coupling.

We think it is helpful to note here that instant preheating would be a dominant mechanism for reheating in the MSSM inflationary model. It was discussed by Kasuya et al.[18] that instant preheating related to Yukawa couplings is efficient in this model. In this case it was suggested that the effect of a A-term is so small that the inflaton exhibits almost straight-line motion on the complex plane. Hence the disturbance of the homogeneous motion caused by the A-term was neglected. In a brane inflationary scenario of “trapped inflation”[19], it has been discussed that open strings stretched between branes play the role of a preheat field. In terms of the brane worldvolume fields the preheat field was identified with massive gauge boson that becomes massless at enhanced symmetry point(ESP). In the scenario of trapped inflation the W boson was assumed to be a stable excitation, however in a MSSM inflationary model gauge bosons can decay into lighter

particles.⁶ If there is a Heisenberg symmetry that protects another flat direction from obtaining $O(H)$ mass during inflation, and also if this direction gives mass to the corresponding preheat field, the impact parameter for the instant preheating $|\phi_2|$ is non-zero and also it has a Gaussian fluctuation that exits horizon during inflation. This is a generic situation in MSSM, which happen if the gauge symmetry is broken in the ϕ_2 direction that is protected by a Heisenberg symmetry. The curvature perturbation generated with the instant preheating is generically important in MSSM chaotic inflationary models, since there are many D-flat and F-flat directions in MSSM Lagrangian.

Despite the novelty of the idea, the actual calculation of the new mechanism is straightforward. The fluctuation of the number density of the preheat field takes precisely the same formula as Eq.(2.6), but the kinetic energy $\dot{\phi}_1$ is different from Eq.(2.9). Due to the quartic term in the inflaton potential, $\dot{\phi}_1$ is given by

$$\dot{\phi}_1^2 \simeq \lambda |\phi_1(t_i)|^4 \simeq 10^4 \lambda M_p^4. \quad (2.15)$$

This relation changes the curvature perturbation obtained in Eq.(2.11) as

$$\zeta \simeq \frac{\alpha 2\pi g |\phi_2(t_*)|^2}{|\dot{\phi}_1(t_*)|} \frac{|\delta\phi_2|}{|\phi_2(t_*)|} \simeq \frac{\alpha g |\phi_2(t_*)|}{M_p} < \alpha g^{1/2} 10 \lambda^{1/4}. \quad (2.16)$$

Hence, the curvature perturbation generated at the end of inflation can be fitted to WMAP data if $\lambda > 10^{-24} g^{-2}$, which gives the “lower bound” for λ . On the other hand, the “standard” curvature perturbation (2.14) generated by an inflaton fluctuation is still very large. Hence we still need to consider a fine-tuning $10^{-24} < \lambda < 10^{-13}$ to suppress the unwanted contribution from an inflaton. As we have presented above, we may use the new mechanism to generate the curvature perturbation in MSSM inflation. The obstacle in the above attempt was the large curvature perturbation generated by an inflaton. In the D-flat inflationary model, we found that this problem is solved only if a fine-tuning is introduced to the coupling constant λ . The parameter λ is protected by the approximate R-parity, which may or may not explain the smallness of λ . The upper bound obtained from phenomenological considerations is consistent with $10^{-24} < \lambda < 10^{-13}$ [18]. As a result, the new mechanism relaxes the severe condition for λ that is related to the magnitude of the R-parity breaking.

⁶In some other cases the amplitude of a oscillation might be much smaller than that in a MSSM chaotic inflation so that the oscillation might be free from efficient reheating induced by instant preheating.

Now our main concern is whether we can construct an MSSM inflationary model in which the conventional curvature perturbation appears as a small value. The reader may know that this task is a piece of cake, but we will examine in detail how this simple idea is realized in MSSM and sneutrino inflationary models.

2.3 Quadratic potential

Perhaps the straightforward extension of the previous example would be to use a quadratic potential instead of the quartic potential. The known example in this direction is sneutrino inflation. Let us first show the known problems and the required fine-tunings in sneutrino inflation, and then show how one can escape from these problems using the new mechanism. Sneutrino is the scalar supersymmetric partner of a heavy singlet neutrino in the minimal seesaw model of neutrino masses. The possibility that inflation was driven by a sneutrino has been discussed by many authors[20]. Following the past studies, we consider chaotic inflation with a $V = \frac{1}{2}m^2\phi^2$ potential. A Heisenberg symmetry is assumed to solve the η -problem. The number of e-foldings N_e is given by

$$N_e = \frac{1}{4} \frac{\phi^2}{M_p^2} \simeq 50, \quad (2.17)$$

which gives the value of ϕ at the beginning of inflation, $\phi(t_i) \simeq 10\sqrt{2}M_p$. The scale of the inflaton potential is normalized by the WMAP data on density fluctuations

$$\zeta \simeq \frac{V^{1/2}}{2\sqrt{6}\pi M_p^2 \epsilon} \simeq 10^{-5}, \quad (2.18)$$

where $\epsilon \equiv \frac{1}{2}M_p^2 \left(\frac{dV/d\phi}{V} \right)^2$ is a slow-roll parameter. From the above equations we can find the required mass as $m \simeq 10^{13}$ GeV, which is within the range of heavy singlet sneutrino masses. The problem in this scenario is that the reheating temperature $T_R \simeq 10^{13}$ GeV is much larger than the bound obtained from the thermal production of gravitinos[21]. It may be possible to make T_R much smaller than the bound, if a neutrino Yukawa coupling Y_ν is much smaller than unity. For example, the reheating temperature becomes as low as $T_R \simeq 10^8$ GeV if the neutrino Yukawa coupling is $|Y_\nu Y_\nu^\dagger| \simeq 10^{-12}$. Otherwise, one should expect an additional late-time entropy production that may be induced by weak inflation. However, if there is a late-time entropy production, the baryon number asymmetry of the

Universe must be produced after the entropy production, which induces another problem in cosmology that may or may not be solved by introducing additional ingredients to the theory[22].

Let us show how this serious condition can be relaxed when the new mechanism is taken into account. Our idea is very simple. Instead of introducing a tiny Yukawa coupling constant, we consider a smaller mass for the sneutrino inflaton. Then, as we have mentioned above for D-flat inflationary model, we can assume that reheating is induced by instant preheating. Any flat direction that gives a mass for the preheat field can play the role of the impact parameter ϕ_2 , provided that the flat direction is protected by a Heisenberg symmetry. Then the dominant contribution comes from Eq.(2.11) if the inflaton mass is smaller than 10^{13}GeV . On the other hand, from Eq.(2.11) the ratio between m and M_p is bounded from “below”, which is given by

$$\frac{m}{M_p} > 10^{-11}. \quad (2.19)$$

This suggests that the inflaton mass m can be as light as $O(10^7\text{GeV})$. In the present case the bound for the sneutrino mass is $10^7\text{GeV} < m \leq 10^{13}$, which is much looser than the condition found in the previous study and is suitable to solve the gravitino problem in sneutrino inflation.

Another important point that we can see from the above analysis is that the inflaton field ϕ_1 can now be identified with a MSSM flat direction itself. In this case the inflaton field ϕ would be the heaviest direction which is rather heavier than a lightest direction ϕ_2 so that inflation ends before the light field ϕ_2 starts to roll down the potential.⁷ A Heisenberg symmetry should protect these flat directions from obtaining $O(H)$ masses during inflation, making the slow-roll inflation possible and at the same time the impact

⁷When one makes predictions in the framework of MSSM, one encounters parameter freedom which is mainly due to soft SUSY breaking terms. The predictive power of the model may be increased if one restricts this freedom, which is the hypothesis called “universality of the soft terms”. Under this assumption one is left with 5 free parameters. However, MSSM with the universal soft masses might not work in practice. Our inflationary scenario supports non-universal soft masses with at least one parameter appears at $O(10^7)\text{GeV}$. This is an interesting possibility that requires further study. See also Ref.[23] in which models with split supersymmetry have been proposed. Alternatively, one may consider some extension of MSSM to include a heavy scalar field.

parameter ϕ_2 can have both an expectation value and a Gaussian fluctuation. If the dominant part of the curvature perturbation is generated at the end of inflation, which may occur if $m < 10^{13}\text{GeV}$, the scale of the potential is not normalized by Eq.(2.18).

2.4 A-term

We would like to make some comments on other inflationary models of MSSM flat direction. Recently it has been pointed out that a MSSM flat direction might support slow-roll inflation with an initial field value much less than the Planck scale M_p and the tree-level potential

$$V(\phi) = m_\phi^2 \phi^2 + A \cos(n\theta + \theta_0) \frac{\phi^{n+3}}{M^n} \quad (2.20)$$

This potential may have a secondary minimum at $\phi_{2nd} = \phi_0 \simeq (m_\phi M_p^{n-3})^{1/(n-2)} \ll M_p$, provided that the coefficient of the A-term satisfies the condition

$$A \geq A_c \equiv 2\sqrt{2(n-1)}m_\phi. \quad (2.21)$$

Moreover, if A takes the critical value A_c the first and the second derivatives of V vanishes at ϕ_0 . If $A = A_c$, the potential near the saddle point is now very flat along the real direction, and it becomes a successful inflaton candidate in MSSM potential[24]. On the other hand, one might think the condition $A = A_c$ is a kind of fine-tuning that must be explained by the underlying (GUT) theory, making the above discussion not within MSSM. We may agree with these critical comments, however the motivation to make inflationary scenarios on MSSM direction is still very strong in this scenario. If the inflaton sector belongs to an unknown (hidden) sector, then there would be too many uncertainties which really hamper the progress not only in particle cosmology but also in GUT phenomenology. On the other hand, if MSSM flat direction could play the role of inflaton, there will be a chance to prove by some observations the existence of such fine-tunings. If the existence of such fine-tunings may be proved by observations, one will be forced to consider a theory behind MSSM that can explain such fine-tunings. Unfortunately, our mechanism for generating curvature perturbations can neither remove nor explain the origin of the condition $A = A_c$, as the condition is needed to make a sufficient number of e-foldings during inflation.

3 Conclusions and Discussions

A new mechanism for generating the curvature perturbation at the end of inflation is discussed in this paper. The dominant contribution to the primordial curvature perturbation may be generated by this new mechanism, which converts isocurvature perturbation of a light field into curvature perturbation during the period of instant preheating. The light field is “not” the inflaton field. Based on this “new inflationary paradigm”, we considered the possibility that chaotic inflation is driven by a MSSM flat direction. We also considered sneutrino inflation as an example for a quadratic inflationary model. Our simple mechanism relaxes some serious constraints that appeared in past studies, making chaotic inflation on a MSSM and a sneutrino direction more plausible than ever before.

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